Testing the Limits

LDT considerations when selecting laser optics

● ▶ **Reflective and refractive optics such as mirrors, windows, lenses, filters, polarizers, and prisms are used to reliably manipulate high energy laser beams. A designer must consider variables such as wavelength, cost, and system geometry to select the appropriate optics to produce highly reliable and robust systems. An often overlooked factor is Laser Damage Threshold (LDT).**

In addition to being monochromatic, directional, and coherent, laser light can emit high energies which can damage optics. Optics for use with lasers often contain dielectric reflective or anti-reflective (AR) coatings consisting of alternating layers of high and low indices which can easily be damaged by the high energy and power densities associated with laser light. Failures in the bulk optical substrate itself are rare. These coatings generally break down before optical materials do.

Damage can manifest in many ways and may be stable or grow in number or size over time, with most failure mechanisms occurring within the coating or at the coating/glass interface. These failure mechanisms can reduce the LDT of an optic by a factor of 100 or more depending on many variables.

LDT testing certifies that optics and their coatings are capable of withstanding the extreme radiation and thermal energy densities of high power lasers without being damaged. Since the laser damage threshold of the optic is typically the limiting factor for the peak power that can be used in a laser system, a close look at LDT is critical before selecting the right components.

How lasers damage an optic

Lasers can damage optical materials in several ways. In transparent materials, non-linear absorption of incident light occurs. For permanent material damage to occur, the material must absorb the laser energy rather than allowing transmission. When continuous wave (CW) lasers are used, damage in optical components is thermally induced, whereas with pulsed lasers, ionization damage mechanisms dominate. There are two nonlinear "excitation" mechanisms that can cause laser energy to be absorbed leading to laser-induced breakdown and damage: photoionization and avalanche ionization.

Photoionization is the direct stimulation of an electron by multiple photons in a laser beam. It can occur at high laser frequencies and intensities when enough energy is absorbed from simultaneous photons, or at lower frequencies when very strong electric fields from the laser suppress the binding of valence electrons to their atoms. When electrons are excited into higher energy bands, the surface structure becomes ionized, either directly causing permanent damage or creating a favorable state for the subsequent failure mechanism to occur.

During avalanche ionization, strong electric fields and the absorption of laser energy simultaneously accelerate electrons. This acceleration causes the electrons to collide with others, knocking more into the conduction band and further ionizing the media, forming a chain reaction. The energy is diffused through the material by thermal conduction, and damage occurs when the temperature becomes high enough for the material to melt or crack. The rate of laser energy absorption and the thermal conductivity of the material together dictate the damage threshold of the optic (Figure 1).

How the LDT of an optic is determined

Pulsed laser damage threshold is measured within the bulk material and on the surface of an optical substrate using various techniques. To determine the point of bulk optical breakdown and damage, differential interference contrast (DIC) and dark field scattering techniques can be used. In this technique, laser energy, pulse duration, and beam profile are measured. The samples are then evaluated using multiple microscopes with different numerical apertures

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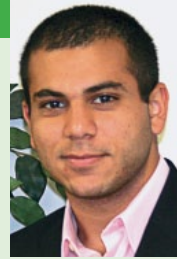
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(NA). Multiple NAs are required to minimize non-linear propagation effects such as self-focusing and aberrations. Corrections to intensity and laser spot size can be made by focusing at an optimal depth.

When optical microscopy with DIC is used to detect bulk material damage, the optics under test are shot with a laser at varying energies and damage is observed using a number of illumination techniques. The energy at which laser transmission begins to drop is the energy threshold for optical breakdown and damage.

The dark field scattering technique can also be used to detect damage at varying laser wavelengths [1]. A pump laser beam is sent into a sample along with a probe laser beam. When damage is produced by the pump laser, light from the probe beam is scattered at a larger angle, collected by a microscope objective, and focused onto a detector.
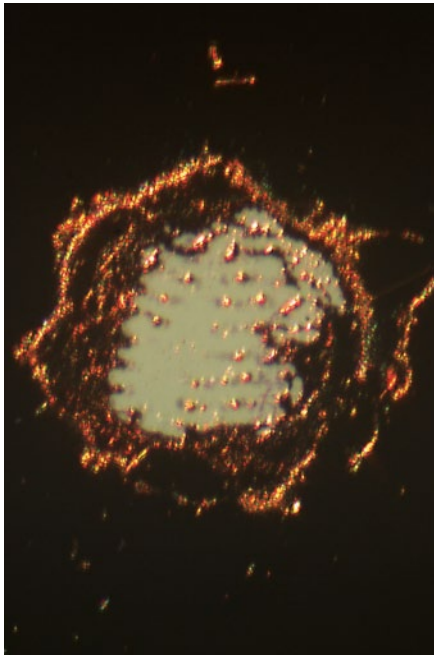
FIG. 1: Pulsed laser-induced damage on a protected gold reflective coating.

Specifications to consider when selecting optics

The laser damage threshold is specified as a power density. Power Density is the power per cross sectional beam area with units of W/cm^2 for CW lasers, or an energy density in J/cm^2 for a specific pulse duration in pulsed lasers.

For CW lasers, if a 1-Watt 1064 nm CW laser has a cross sectional beam area of $2 cm^2$, the power density would be calculated as in Equation 1:

$$PD = \frac{1W}{2cm^2} = 0.5 \ W/cm^2$$

For pulsed lasers, the units for LDT are similar, but due to the time component in Power, it is inconvenient to describe the power of a laser with a duty cycle, hence the industry convention is to use units of energy instead of power, which is a rate of expending energy. Energy density is the energy per cross sectional beam area for a specific pulse duration. Therefore, if a 1 Joule, 10ns 1064 nm pulsed laser has a cross sectional beam area of $2 cm^2$, the energy density would be calculated as in Equation 2:

$$ED = \frac{1J}{2cm^2} = 0.5 \ J/cm^2 \text{ at 10ns pulse width}$$

Theoretically, since the energy of a photon is inversely proportional to the wavelength, the energy and power densities linearly scale as a function of wavelength as represented by Equation 3:

$$PD_{(y)} = PD_{(x)} \frac{\lambda_y}{\lambda_x}$$

where $PD_{(y)}$ is the Power or Energy Density at the new wavelength, $PD_{(x)}$ is the Power or Energy Density at the old wavelength, λ_y is the new wavelength and λ_x is the old wavelength.

This general rule of thumb makes it easy to determine if a laser can be used without damaging the optic, when the LDT rating is provided for a wavelength other than the one intended to be used. A laser with a power density of $2 W/cm^2$ at 1064 nm can be used with an optic rated at $1 W/cm^2$ at 532 nm, $0.667 W/cm^2$ at 355 nm, etc. with a minimum probability of damaging the optic.

Newton's square-root scaling factor can be used to determine whether a laser can be used with an optic that is not rated at the same pulse duration. Equation 4 offers a new LDT for the new pulse duration:

$$LTD(y) = LDT(x) \sqrt{\frac{t_y}{t_x}}$$

where LTD(y) is the new Laser Damage Threshold for laser y, LDT(x) is the original laser damage threshold for laser x, t_y is the pulse duration for laser y, and t_x is the pulse duration for laser x.

For example, an Edmund Optics TECH-SPEC Laser Line Non-polarizing Plate Beamsplitter has a laser damage threshold of $3 \ J/cm^2$ at 532 nm for a 10ns pulse duration. For someone with a 532 nm laser with a 20ns pulse, the new laser damage threshold would be approximately $4.3 J/cm^2$ according to the calculation in Equation 5:

$$LTD(10 ns) = 3 \frac{J}{cm^2} \sqrt{\frac{20 \times 10^{-9} \ sec}{10 \times 10^{-9} \ sec}} \approx 4 \frac{J}{cm^2}$$

For longer pulse durations, a higher LDT can be expected. Typically, shorter pulses will have higher peak powers than longer pulses. So, optics can generally be exposed to larger energy densities at longer pulse durations.

LDT Dependence on Variables of Optic Manufacturing

Understanding the LDT of coated optics is not an exact science. It is not always straightforward, and involves many variables that are difficult to control. Empirical studies completed at Edmund Optics on LDT have formed a set of trends or "Rules of Thumb" to keep in mind when selecting optics with or without coatings:

- Metallic coatings exhibit binary performance when it comes to LDT. They withstand the energy density and can suddenly exhibit total marked damage when they fail.
- Dielectric or multilayer coatings generally have a slower failure rate when compared to metallic coatings, with damage beginning slowly as the probability of damage increases.
- Empirical data show that under certain conditions LDT scales linearly by wavelength. Higher damage thresholds have been seen for pulsed lasers at longer wavelengths.
- LDT may have a dependence on the energy gap between the energy levels, with larger band gaps displaying higher LDT. However, this trend changes when non-linear optical effects start to manifest in the bulk optical substrate.
- How the surface is prepared before coatings are applied to optics is important. LDT is also highly dependent on composition and other factors of applying optical coatings and the materials involved in their manufacture for use.

Other guidelines stem from those involved with optics testing, such as observations that some substrate glasses react when exposed to the atmosphere, heavily affecting the optics' LDT. Maintaining the highest damage thresholds on reactive glasses require that they be stored in inert gases or immersed in a solution.

Various deposition processes used to apply anti-reflective and other coatings on an optical substrate can affect LDT. Most commonly, silica or other glass substrates receive deposition in a cleanroom using technologies such as, Electronic beam (E-beam), Ion Assisted Deposition (IAD), Plasma Assist, Ion Beam Sputtering (IBS), Magnetron Sputtering, Sputtering with Oxidation Enhancement, Chemical Vapor Deposition, Sol Gel, Laser Deposition, or Atomic Layer Deposition.

When reviewing published LDT specifications for an optic or optical coating, it is important to understand that the factors summarized in Table 1 can influence LDT values and how they were determined. Damage results can be skewed by the factors in the "Laser Variables" column. Precise measurements of these parameters allow for more accurate evaluation. The "Substrate Variables" column indicates inherent properties of optical materials and how they are prepared. The "Coating Variables" column indicates the most important factors known to affect LDT during the coating manufacturing process. Factors in the "Testing Variables" column are important to ensure precise damage results during single and multiple shot testing, which typically follow standardized methods specified by ISO Document 11254 Parts 1 and 2.

Laser damage competition confirms correlation to manufacturing processes

The 2008 Boulder Thin Film Damage Competition [2] confirmed that certain coating deposition processes and materials consistently produced optics with higher laser damage thresholds than others. Laser resistant IR laser mirror coatings were tested at the 2008 XL Annual Boulder Damage Symposium. Private, university, and government participants submitted 35 coated silica samples to an independent laser damage testing service, specifying the number of coating layers, materials, deposition methods, and spectral performance.

Samples were double-blind tested with the same thin film damage setup, testing protocols, and testing area specified by Borden [3] et al. in his paper, "Improved method for laser damage testing coated optics," with the resulting laser damage in the coating classified into three categories:

- No Damage.
- Initiation – pinpoint damages were observed to occur sized <100 µm in less than 1 % of the sites, and they did not grow upon repeated illumination.
- Failed – either pinpoint damage occurred on >1 % of the sites with a size >100 µm, or the number or size of the damage sites grew upon further illumination.

Note that in some applications, stable pinpoint damage may be tolerable.

Results of the study indicated that a wide range of laser resistance exists in deposited thin film coatings. The highest laser resistant films were deposited by e-beam, however, other deposition technologies such as IAD, IBS, and plasma assist also produced excellent laser resistance. Plasma etching may be

FIG. 2: An example of a high energy laser setup where LDT considerations of the optics is crucial.

TABLE 1: Factors affecting LDT.

Laser Variables	Substrate Variables	Coating Variables	Testing Variables
Pulse Duration	Material	Deposited Material	Calibration of Testing Equipment
Pulse Repetition Rate	Surface Quality	Substrate Material	Laser Focus Position
Beam Intensity Shape	Reactivity to environment	Deposition Process	Operator Ability to Detect Damage
Beam Quality	Cleanliness and the ability for an optic to be cleaned	Pre-Coating Preparation and Cleaning	Test Method – Raster Scan vs. Random Points
Beam Diameter	Material Absorption	Run-to-Run Control	
Wavelength	Thermal Diffusivity	Protective Layers	
	Material Inhomogeneity	Coating Design and Optimization	
	Material Defects		

beneficial for high laser resistance through better film adhesion to the substrate.

Films containing Hafnia tended to yield the most laser resistance, and oxides such as Hafnium Oxide, Tantalum Oxide, and Silicon Dioxide, performed better than metallic films at the wavelength and pulse length tested. Overcoats, that are usually referred to as an absentee layer based off of a half wave design, were helpful for HfO_2/SiO_2 coatings, but not Ta_2O_5/SiO_2 coatings.

Conclusion

Understanding the different damage mechanisms that contribute to the LDT of an optic is critical when an optical system including a high power laser is being designed. Anticipating the effects of these variables can avoid unforeseen system failures ensur-

ing the reliability and robustness of the optical system throughout its life span.

References

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[3] *Borden et al.,* "Improved method for laser damage testing coated optics," SPIE 5991, 59912a-1-8, 2006.